The Science Frontier

Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics

Science Questions and Discovery Areas of the Five Science Frontier Panels

Martha Haynes
Vice Chair Astro2010

Astro2010: Science First

- The Astro2010 program is **driven** by its **science** goals.
- The Science Frontier Panels were organized and got to work early in the process.
- The outcome of their deliberations then informed the Program Prioritization panels and the main Astro2010 committee.
- The NWNH program can be directly traced to the SFP reports.

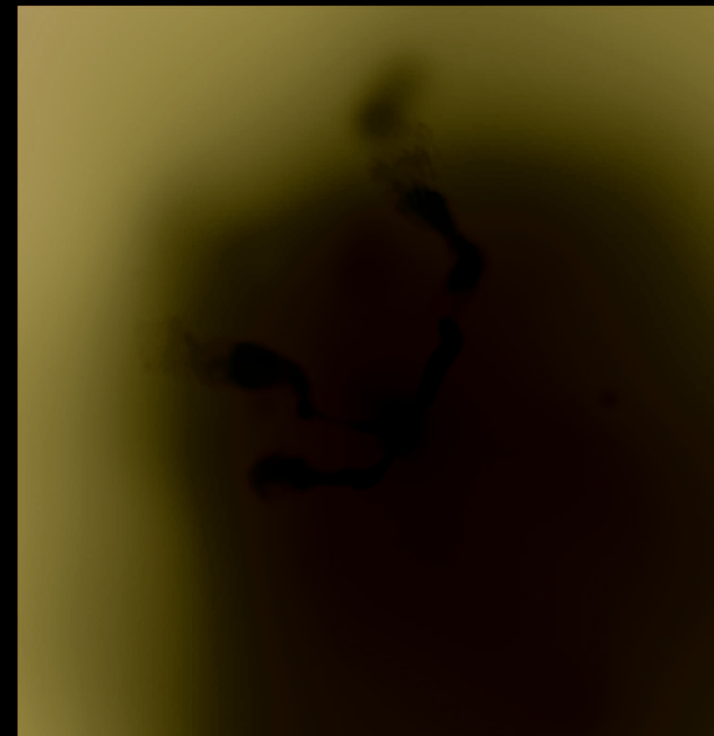

FIGURE 2.2 The source 3C 75, shown here in X-rays (blue) and radio waves (pink), is a rare exampl of two galaxies caught in the act of merging. Not only do their stars merge, but their central blac holes—each producing a pair of jets containing gas moving outward at a speed close to that o light—also will do likewise in perhaps a few hundred million years. Many similar mergers involvin smaller black holes in the nuclei of younger galaxies are thought to have taken place. When black hole coalesce, they create intense bursts of gravitational radiation. SOURCE: X-ray—NASA/CXC/AIfA/D Hudson and T. Reiprich et al. Radio—NRAO/VLA/NRL.

Science Frontier Panels: Dividing A&A by Five

Cosmology and Fundamental Physics (CFP) - David Spergel

- Early universe, microwave background, reionization and galaxy formation up to virialization of protogalaxies. Large scale structure, intergalactic medium, determination of cosmological parameters, dark matter, dark energy. High energy physics using astronomical messengers, tests of gravity, physical constants as determined astronomically.

The Galactic Neighborhood (GAN) - Mike Shull

- Structure and properties of nearby galaxies including the Milky Way and their stellar populations, interstellar media, star clusters. Evolution of stellar populations.

Galaxies across Cosmic Time (GCT) - Meg Urry

- Formation and evolution of galaxies and galaxy clusters, active galactic nuclei and QSOs, mergers, star formation rate, gas accretion, global properties of galaxies and galaxy clusters, supermassive black holes.

Planetary Systems and Star Formation (PSF) - Lee Hartmann

- Solar system bodies (other than the Sun) and extrasolar planets, debris disks, exobiology, formation of individual stars, protostellar and protoplanetary disks, molecular clouds and the cold ISM, dust, and astrochemistry.

Stars and Stellar Evolution (SSE) - Roger Chevalier

- The Sun as a star, stellar astrophysics, structure and evolution of single and multiple stars, compact objects, supernovae, gamma-ray bursts and solar neutrinos. Extreme physics on stellar scales.

Science Frontier Panel on Cosmology and Fundamental Physics (CFP)

DAVID N. SPERGEL, Princeton University, *Chair*,
DAVID WEINBERG, Ohio State University, *Vice Chair*
RACHEL BEAN, Cornell University
NEIL CORNISH, Montana State University
JONATHAN FENG, University of California, Irvine
ALEX V. FILIPPENKO, University of California, Berkeley
WICK C. HAXTON, University of California, Berkeley
MARC P. KAMIONKOWSKI, California Institute of Technology
LISA RANDALL, Harvard University
EUN-SUK SEO, University of Maryland
DAVID TYTLER, University of California, San Diego
CLIFFORD M. WILL, Washington University

Science Frontier Panel on the Galactic Neighborhood (GAN)

MICHAEL J. SHULL, University of Colorado, *Chair*
LEO BLITZ, University of California, Berkeley
JULIANNE DALCANTON, University of Washington
BRUCE T. DRAINE, Princeton University
ROBERT FESEN, Dartmouth University
KARL GEBHARDT, University of Texas
JUNA KOLLMEIER, Observatories of the Carnegie Institution of Washington
CRYSTAL MARTIN, University of California, Santa Barbara
JASON TUMLINSON, Space Telescope Science Institute
DANIEL WANG, University of Massachusetts
DENNIS ZARITSKY, University of Arizona
STEPHEN E. ZEPF, Michigan State University

Science Frontier Panel on Galaxies Across Cosmic Time (GCT)

C. MEGAN URRY, Yale University, *Chair*
MITCHELL C. BEGELMAN, University of Colorado, *Vice Chair*
ANDREW J. BAKER, Rutgers University
NETA A. BAHCALL, Princeton University
ROMEEL DAVÉ, University of Arizona
TIZIANA DI MATTEO, Carnegie Mellon University
HENRIC S.W. KRAWCZYNSKI, Washington University
JOSEPH MOHR, Ludwig Maximilian University
RICHARD F. MUSHOTZKY, NASA Goddard Space Flight Center
CHRISTOPHER S. REYNOLDS, University of Maryland
ALICE SHAPLEY, University of California, Los Angeles
TOMMASO TREU, University of California, Santa Barbara
JAQUELINE H. VAN GORKOM, Columbia University
ERIC M. WILCOTS, University of Wisconsin

Science Frontier Panel on Planetary Systems and Star Formation (PSF)

LEE W. HARTMANN, University of Michigan, *Chair*
HECTOR ARCE, Yale University
CLAIRE CHANDLER, National Radio Astronomy Observatory
DAVID CHARBONNEAU, Harvard University
EUGENE CHIANG, University of California, Berkeley
SUZAN EDWARDS, Smith College
ERIC HERBST, Ohio State University
DAVID C. JEWITT, University of California, Los Angeles
JAMES P. LLOYD, Cornell University
EVE C. OSTRIKER, University of Maryland
DAVID J. STEVENSON, California Institute of Technology
JONATHAN C. TAN, University of Florida
DAN M. WATSON, University of Rochester

Science Frontier Panel on Stars and Stellar Evolution (SSE)

ROGER A. CHEVALIER, University of Virginia, *Chair*
ROBERT P. KIRSHNER, Harvard-Smithsonian Center for Astrophysics, *Vice Chair*
DEEPTO CHAKRABARTY, Massachusetts Institute of Technology
SUZANNE HAWLEY, University of Washington
JEFFREY R. KUHN, University of Hawaii
STANLEY OWOCKI, University of Delaware
MARC PINSONNEAULT, Ohio State University
ELIOT QUATAERT, University of California, Berkeley
SCOTT RANSOM, National Radio Astronomy Observatory
HENDRIK SCHATZ, Michigan State University
LEE ANNE WILLSON, Iowa State University
STANFORD E. WOOSLEY, University of California, Santa Cruz

Charge to the Panels

Cosmology and Fundamental Physics Statement of Task

The Cosmology and Fundamental Physics (CFP) Panel will identify and articulate the scientific themes that will define the frontier in CFP research in the 2010-2020 decade. Its scope will encompass cosmology and fundamental physics, including the early universe, the microwave background, the reionization and galaxy formation up to virialization of protogalaxies, large scale structure, the intergalactic medium, the determination of cosmological parameters, dark matter, dark energy, tests of gravity, astronomically determined physical constants, and high energy physics using astronomical messengers. Its assessment will play a key role in the Astronomy and Astrophysics 2010 study, which will survey the field of space- and ground-based astronomy and astrophysics, recommending priorities for the most important scientific and technical activities of the decade 2010-2020. The CFP Panel will prepare a report that will identify the scientific drivers of the field and the most promising opportunities for progress in research in the next decade, taking into consideration those areas where the technical means and the theoretical foundations are in place for major steps forward.

More broadly, this panel will be charged (as will each of the five science panels) with the following tasks:

1. Identify new scientific opportunities and compelling scientific themes that have arisen from recent advances and accomplishments in astronomy and astrophysics;
2. Describe the scientific context of the importance of these opportunities, including connections to other parts of astronomy and astrophysics and, where appropriate, to the advancement of our broader scientific understanding.
3. Describe the key advances in observation and theory necessary to realize the scientific opportunities within the decade 2010-2020; and
4. Considering the relative compelling nature of the opportunities identified and the expected accessibility of the measurement regimes required, call out up to four central questions that are ripe for answering and one general area where there is unusual discovery potential and that define the scientific frontier of the next decade in the SFP's sub-field of astronomy and astrophysics.

In completing this task, each Science Frontier Panel will provide the Astronomy and Astrophysics 2010 Committee's Subcommittee on Science with its inputs in the Spring of 2009 and complete its panel report thereafter. The panel reports will be published following the release of the main survey committee's report in 2010. The Subcommittee on Science will issue a request for community input to ensure broad community participation in the process of identifying the scientific frontiers.

Charge to the Panels

More broadly, this panel will be charged (as will each of the five science panels) with the following tasks:

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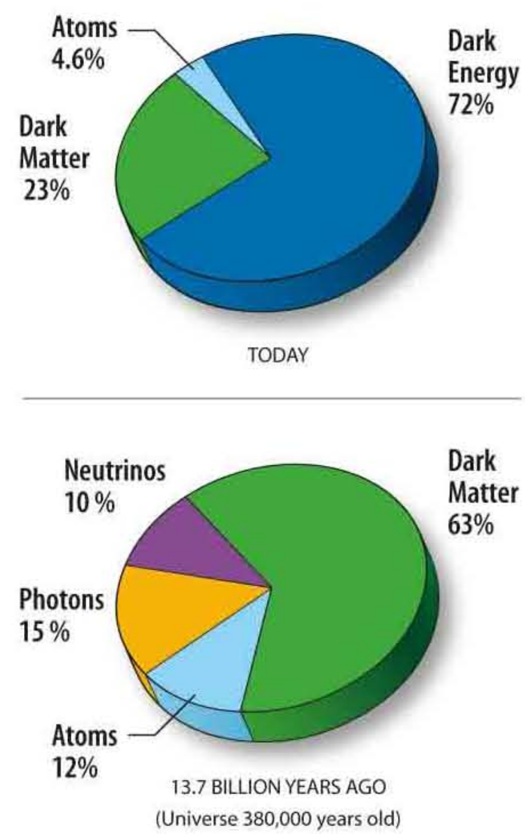
Deliberate instruction: **be selective**
No "shopping lists"

Disclaimer: I must select even further!

Science Frontier Panel on Cosmology and Fundamental Physics (CFP)



Questions:

- How did the universe begin?
- Why is the universe accelerating?
- What is dark matter?
- What are the properties of the neutrino?

Discovery area:

- Gravitational wave astronomy

Cosmology and Fundamental Physics (CFP)

- The CMB
- Weak lensing
- Dark Age HI
- Billion Galaxy HI survey

BOX 1.1
Conclusions on Inflation and Acceleration
by the Science Frontiers Panel on Cosmology and Fundamental Physics

Goals:

- Measure the amplitude of the initial scalar fluctuations across all observationally accessible scales through measurements of CMB E-mode polarization, the LSS of galaxies, weak lensing of galaxies and the CMB, and fluctuations in the intergalactic medium.
- Search for ultra-long-wavelength gravitational waves through measurements of CMB B-mode polarization, achieving sensitivities to the tensor-scalar ratio at the level set by astronomical foregrounds.
- Search for isocurvature modes, non-Gaussian initial conditions, and other deviations from the fluctuations predicted by the simplest inflationary models.
- Measure the curvature of the universe to precision of 10^{-4}, the limit set by horizon scale fluctuations.
- Determine the history of cosmic acceleration by measuring the distance-redshift relation and Hubble parameter to sub-percent accuracy over a wide range of redshifts.
- Determine the history of structure growth by measuring the amplitude of matter clustering to sub-percent accuracy over a wide range of redshifts.
- Improve measurements that test the constancy of various physical constants and the validity of general relativity.

Needed capabilities:

- CMB experiments that measure E-mode polarization out to the limits set by foregrounds.
- CMB experiments that measure B-mode polarization, both for tensor modes and for lensing. These should begin with ground-based and balloon experiments with a variety of techniques, which can probe to $T/S \approx 10^{-2}$, and eventually proceed to space-based experiments, which may reach $T/S \approx 10^{-3}$ or below.
- Supernova campaigns that provide high-quality observations of several thousand Type Ia supernovae, including rest-frame IR photometry.
- Weak lensing surveys with accurate shape measurements and photometric redshifts of $\sim 10^9$ galaxies.
- Spectroscopic redshift surveys of $\sim 10^8$ galaxies.
- Measurements of small-scale structure in the intergalactic medium, from the Lyman-α forest and from pre-reionization 21-cm radiation.
- Significant improvements in precision tests of general relativity and time-variation of fundamental "constants."

Cosmology and Fundamental Physics (CFP)

- Dwarf galaxy dynamics
- Detection of UHE neutrinos

BOX 1.3
Conclusions Regarding Neutrinos
by the Science Frontiers Panel on Cosmology and Fundamental Physics

Goals:

- Develop the sensitivity to detect and study ultra-high-energy neutrinos expected if the cosmic-ray energy cutoff is due to protons annihilating into neutrinos and other particles. The detection of UHE neutrino fluxes above those expected from the GZK mechanism would be the signature of new acceleration processes.
- Measure the neutrino mass to a level of 0.05 eV, the lower limit implied by current neutrino mixing measurements, through its effects on the growth of structure.
- Enable precision measurement of the multi-flavor neutrino "light curves" from a Galactic supernova.

Improve measurements of light-element abundances in combination with big bang nucleosynthesis theory to test neutrino properties and dark matter models

Needed Capabilities:

- Measurements of small-scale structure from dwarf-galaxy dynamics, gravitational lensing, and the Lyman-α forest.
- Precision measurements of the power-spectrum amplitude using a combination of CMB lensing, weak lensing, the galaxy power spectrum, and measurements of neutral hydrogen fluctuations.
- Neutrino detectors that can measure the time, energy, and flavor distribution of neutrinos from a nearby supernova and detect the integrated supernova neutrino background.
- Radio-frequency experiments for UHE neutrinos, with sensitivity to detect the expected events associated with the proton GZK cutoff.
- Improved characterization of the energy spectrum and sources of cosmic rays near the GZK cutoff.
- Improved measurements of light-element abundances in stellar atmospheres and the interstellar and intergalactic medium, principally through high-resolution spectroscopy on ~30-m telescopes.

Cosmology and Fundamental Physics (CFP)

- Pulsar timing
- High energy source followup
- Radio transients

BOX 1.4
Conclusions Relating to Gravitational-Waves
by the Science Frontiers Panel on Cosmology and Fundamental Physics

Goals:

- Detect gravitational waves from mergers of neutron stars and stellar mass black holes.
- Detect gravitational waves from inspiral and mergers of supermassive black holes at cosmological distances.
- Achieve high signal-to-noise ratio measurements of black hole mergers to test general relativity in the strong field, highly dynamical regime.
- Identify electromagnetic counterparts to gravitational-wave sources.
- Open a radically new window on the universe, with the potential to reveal new phenomena in stellar-scale astrophysics, early-universe physics, or other unanticipated areas.

Needed Capabilities:

- A space-based gravitational wave interferometer probing the 10^{-5}–10^{-1} Hz frequency range to the sensitivity limits imposed by astrophysical "foreground" noise from Galactic binaries.
- Ground-based interferometers probing the 10–1000 Hz range with the sensitivity to detect neutron star mergers at 300 Mpc distances.
- Pulsar-timing arrays probing the nanoHz frequency range with the sensitivity to detect the stochastic background from supermassive black hole binaries.
- Time-domain electromagnetic facilities with the sensitivity, speed, and flexibility needed to find the counterparts of gravitational wave sources.

Science Frontier Panel on the Galactic Neighborhood (GAN)

Questions:

- *What are the flows of matter and energy in the circumgalactic medium?* This question concerns the understanding of the circumgalactic medium that is needed to understand the mass, energy, and chemical feedback cycle that appears to shape the growth of galaxies and the metal enrichment of the universe. In this report the panel identifies a program of detailed observations of the accretion and outflow processes in nearby galaxies that can inform the understanding of these processes at all epochs and mass scales.
- *What controls the mass-energy-chemical cycles within galaxies?* This question explores the rich system of gas and stellar physics that shapes, and is shaped by, the interstellar medium. The panel outlines multiwavelength and theoretical studies of gas, dust, and magnetic fields within galaxies. Such studies can unravel the complexities of the gaseous ecosystem, with a level of detail critical to isolating the relevant physics but that cannot be obtained outside the galactic neighborhood.
- *What is the fossil record of galaxy assembly from first stars to present?* This question focuses on probes of the fossil record of star formation, galaxy assembly, and the first stars. The panel identifies the value of surveys for resolved stars at high spatial resolution, with spectroscopic follow-up of stellar populations and metal-poor halo stars providing high-impact science unique to the galactic neighborhood. Furthermore, this fossil record promises to reveal the properties of galaxies at epochs where they cannot be seen directly.
- *What are the connections between dark and luminous matter?* This question addresses the use of the galactic neighborhood as a laboratory of fundamental physics. The local universe offers the opportunity to isolate the nearest and smallest dark matter halos and to study astrophysically "dark" systems at high spatial resolution. The panel discusses the many observational and theoretical advances that could be expected as a result of these unique capabilities.

The Galactic Neighborhood (GAN)

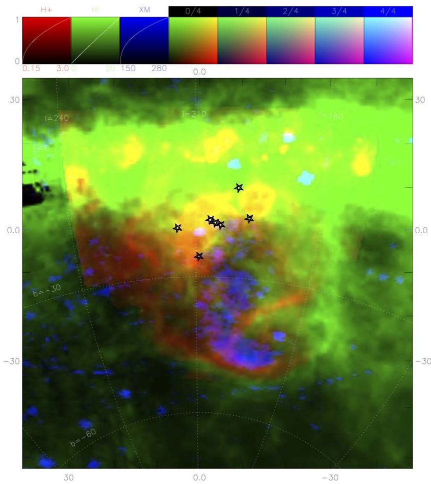


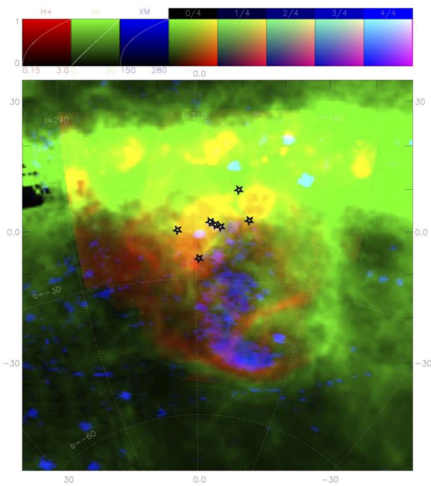
FIGURE 2.3 Large-scale image of the Orion-Eridanus superbubble (~5000 deg^2) showing X-rays in blue (ROSAT), H II in red (WHAM), and H I in green as well as the brightest stars in Orion for scale. This image shows the importance of large-scale multi-wavelength surveys for elucidating structures in the Milky Way ISM. X-rays arise from hot gas heated by supernova explosions that sweep up cool H I. SOURCE: Courtesy of Carl Heiles, University of California, Berkeley.

- Studies of dust and gas in MW and other galaxies

Multiwavelength observations are required to characterize the ISM–IGM complexity:

- *Sensitive, high resolution, all-sky 21 cm emission surveys* out to $z = 0.1$ will be possible with the Allen Telescope Array (ATA) if it is expanded to at least 128 and perhaps 256 dishes. The Expanded Very Large Array (EVLA) will be able to survey smaller portions of the sky in HI at yet higher angular resolution, and the Green Bank Telescope (GBT) equipped with array receivers can survey the sky at more modest resolution, as can Arecibo with an upgrade to the number of 21-cm receivers it currently has. These telescopes will be able to survey the Milky Way, galaxies out to moderate redshifts, as well as H I in the IGM. They will be able to determine the H I distribution and kinematics as well as the spin temperature on sightlines with background radio sources. The goal is to map $\geq 3\pi$ steradians over the space of several years with 10 km s^{-1} velocity resolution and ~1000 deg^{2}with 1km s^{-1} spectral resolution, 1 arcmin spatial resolution, 20,000 km s^{-1} velocity range. These facilities should be able to achieve $\sigma(T_A)$ = 0.5 K per pixel and have bandwidth sufficient to map ~1000 deg^2 to $z = 0.5$ in a few years of observation.
- *Millimeter and submillimeter-wave observations of molecular lines and dust continuum in nearby galaxies* using large single-dish telescopes and millimeter-wave arrays equipped with array receivers (in particular CARMA) will be needed for mapping large areas at high resolution. ALMA will be incomparable for high-resolution, high-sensitivity mapping of small areas and for high molecular-line transitions and dust continuum. These telescopes will characterize the distribution and kinematics of molecular gas in structures including individual clouds, giant molecular clouds (GMCs), and dense gas in galactic centers that is likely fuel for energetic activity to the distribution of star-forming gas and dust in galaxies to $z = 0.1$. For high-resolution mapping, ALMA will be unsurpassed as long as the present plan to build at least 50 telescopes is maintained. However, the field-of-view is small, especially at higher frequencies (~5–25 arcsec). Therefore, array receivers and bolometric cameras with a large number of elements should be developed for deployment on CARMA, GBT, LMT so that they may be ultimately installed on ALMA and future large single-dish facilities.
- *All-sky maps from Akari, Planck, and WISE* will provide new views of the distribution of thermally-emitting dust on arcminute scales. Since dust and gas are tightly coupled, the dust morphology reveals the distribution of the gas. Spitzer has surveyed star-formation throughout the Milky Way and many external galaxies. Herschel (3.5m aperture) will provide detailed images of selected regions, but a large (~20m aperture) submm telescope at a high-altitude site would allow high resolution mapping at 350 µm. A 5–10 m cryogenic submm telescope in space would permit dust continuum imaging with better resolution and much greater sensitivity than Herschel.

The Galactic Neighborhood (GAN)



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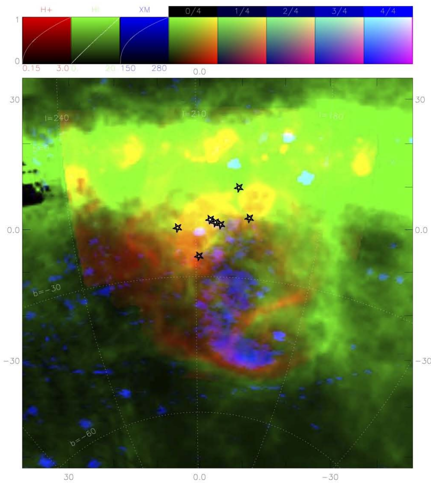
- Zeeman studies
- Faraday rotation studies
- All-sky C-band survey

What is the Structure of the Magnetic Field in the ISM?

Magnetic fields are dynamically important in the ISM: strong enough to control gas motions in H I clouds and star-forming molecular clouds and to affect outflows from the disk into the CGM. While present-day knowledge of magnetic fields in galaxies remains sparse, technological developments now permit observational progress:

- *Starlight polarimetry* using visual wavelengths for diffuse regions, and infrared (K-band) for dense clouds can provide detailed maps of the magnetic field within individual clouds. This will require construction of imaging polarimeters for large telescopes at V, K, and possibly other wavelength bands.
- *Polarimetry of far-infrared/submm emission from dust.* Planck will provide all-sky maps of polarized submm emission from dust on 5 arcmin scales in bright regions, and on ~1 degree scales from the average infrared "cirrus." New instruments such as SCUBA II and ALMA will be able to map the polarized emission from dust in molecular clouds and protostellar disks. Future instruments may permit far-infrared polarimetry from SOFIA. These maps, combined with other data, will disclose the three-dimensional structure of the magnetic field within a few hundred pc of the galactic plane and reveal the projected magnetic field structure in nearby galaxies.
- *Zeeman effect* using H I, OH, and CN to determine magnetic field strengths in atomic and molecular gas. High-resolution all-sky surveys are now possible with radio interferometers. This requires polarization purity of 20 dB and velocity resolution of 0.1 km s^{-1}. The sensitivity and resolution are the same as for all-sky H I surveys given above.
- *Faraday rotation* using pulsars and AGN to probe the line-of-sight component of the magnetic field weighted by the electron density. Ultra-high bandwidth instrumentation and radio telescopes, now being developed for all-sky Zeeman measurements, will be suitable for Faraday rotation studies.
- *Microwave synchrotron emission.* The C-Band All Sky Survey will produce an all-sky map of polarized synchrotron emission near 5 GHz, where Faraday depolarization is modest, revealing the (projected) galactic magnetic field on ~1 deg scales.

The Galactic Neighborhood (GAN)



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- MHD/shock theory
- Studies of dust
- Laboratory astrophysics

Microphysics of the ISM

To understand how galaxies form out of gas, it is necessary to improve our theoretical understanding of the important dynamical processes. Critical areas include:

- *MHD and plasma physics theory.* MHD simulations are increasing in sophistication and spatial resolution, but still lack accurate representations of "sub-grid" phenomena such as decay of turbulence, magnetic reconnection, and ambipolar diffusion. Theoretical work must focus on these fundamental processes, and key questions are: *What processes are responsible for generating galactic magnetic fields? How does the field evolve?*
- *Shock waves.* Shock waves are ubiquitous in the interstellar and IGM, but there are still gaps in our theoretical understanding of phenomena including: the structure of collisionless shocks; cosmic ray acceleration in shocks; magnetic field amplification in fast shocks; coupling between T_e and T_i in collisionless shocks; thermal conduction; multi-fluid MHD shocks in neutral clouds; and the role of charged dust grains.
- *Interstellar dust.* Interstellar dust is important because of its role in attenuating and scattering light, its dynamical effects, and its value as a diagnostic tool (tracer of the gas, emission spectra sensitive to the local starlight intensity, and polarized emission and extinction sensitive to the local magnetic field). Using aligned dust as a tracer for magnetic fields requires understanding the shapes and optical properties of dust grains and how variations in the degree of dust alignment depend on local conditions in clouds. The composition of dust varies within the Milky Way, and between galaxies; it needs to be understood why. Observational studies, ranging from microwaves (emission from spinning dust) to X-rays (scattering and absorption by dust), provide a growing array of observational constraints which, together with advances in theory, will result in increasingly realistic grain models during the coming decade.
- *Atomic physics and laboratory astrophysics.* Astrophysics is dependent on accurate wavelengths and oscillator strengths, photoionization and photodissociation cross sections, and rate coefficients for radiative recombination, dielectronic recombination, charge exchange, and collisional excitation. For example, there appears to be a factor-of-two uncertainty in the oscillator strength for the semi-forbidden line, C II] 2325Å, normally used to determine the gas-phase carbon abundance. Next-generation X-ray facilities, as well as ALMA mm-studies, will require more accurate wavelengths for lines, as well as more accurate X-ray absorption coefficients for likely astrophysical solids. Some quantities can be obtained from calculations, but others may only be obtained from laboratory measurements. It is reasonable to suspect that PAHs might account for the diffuse interstellar bands, but only careful measurement of PAH absorption cross sections in the gas phase in the lab can confirm and quantify this. Lab measurements are also needed for photoelectric yields from dust grains over a range of sizes, including PAHs.

The Galactic Neighborhood (GAN)

DISCOVERY AREAS

GAN D1. Time-Domain Astronomy as Galactic Neighborhood Area of Discovery Potential

The panel views the exploration of the transient sky, where enormous swaths of parameter space remain essentially virgin territory, a potent area of discovery. New areas of parameter space have always led to new discoveries and there is every reason to think that examining the sky on timescales from nanoseconds to years across the entire electromagnetic spectrum will led to new significant scientific discoveries and insights. Moreover, the availability of new instruments, along with ever increasing computational capability and algorithm development, makes the transient sky an area particularly ripe for transforming our basic understanding regarding the content of the galactic neighborhood.

GAN D2. Astrometry as a General Area of Discovery Potential

Astrometry can open a new window for the discovery of extrasolar planets, discover and characterize vast numbers of Kuiper Belt objects, asteroids, and comets, test the weak-field limit of general relativity with unprecedented precision, and measure the aberration of quasars from the centripetal acceleration of the Sun by the galaxy. These surveys can provide a complete inventory of stars near the Sun, with accurate masses for a wide range of stars, particularly rare objects at the extremes of the Hertzsprung-Russell diagram. They can measure orbits of the globular clusters and satellite galaxies of the Milky Way and galaxies of the Local Group and fix properties of the major stellar components of the Milky Way. The most important tools are large-scale photometric, spectroscopic, and astrometric surveys. Prototypes in past decades were 2MASS, SDSS, IRAS, and Hipparcos. Larger, deeper, more accurate surveys have exceptional discovery potential next decade, largely from the variety of powerful astrometric techniques now reaching maturity:

The Galactic Neighborhood (GAN)

- Maser astrometry in MW, Local Group and beyond
- Astrometry of SgrA*

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1. Radio astrometry of masers in massive star-forming regions yields accuracies of a few microarcseconds (μ as). These measurements yield: (1) accurate (few per cent) distances and velocities for ~20 objects several kpc away; (2) estimates of the distance to the galactic center; and the rotation speed of the Local Standard of Rest that are arguably the most accurate available; (3) the first proper motions of galaxies other than the Milky Way and its satellites. Radio astrometry of maser sources in AGN accretion disks provide the best masses for black holes at the centers of galaxies, with the possibility of many more, and offers the prospect of determining the extragalactic distance scale (the Hubble constant) with unmatched precision.
2. Radio astrometry of the source Sgr A*, believed to coincide with the black hole at the galactic center, now yields the most accurate measurement of the angular speed of the Sun in its galactic orbit, as well as strong constraints on the mass of the black hole and the mass and orbit of any possible companion black hole(s). Infrared astrometry of the stars around Sgr A* proves that it really is a black hole rather than a compact stellar cluster, and gives its mass and distance at steadily growing precision.
3. Space-based optical astrometry is capable of achieving astrometric accuracies of a few micro arcseconds on hundreds of target stars or ~20 μas for over 10 million stars, as will be done with GAIA.
4. Time-resolved ground-based astrometry using large optical surveys can provide proper motions and photometric parallaxes for millions of stars, and identify unusual high-proper-motion objects that may be faint nearby stars and hypervelocity stars.

Science Frontier Panel on Galaxies Across Cosmic Time (GCT)

Questions:

- How do cosmic structures form and evolve?
- How do baryons cycle in and out of galaxies, and what do they do while they are there?
- How do black holes grow, radiate, and influence their surroundings?
- What were the first objects to light up the universe and when did they do it?
- *Unusual discovery potential*: the epoch of reionization.

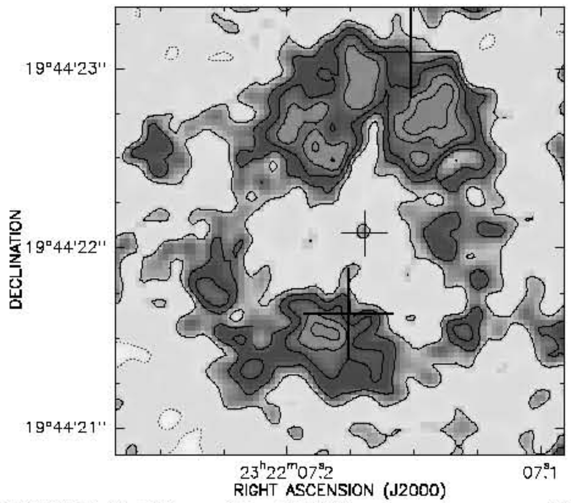


FIGURE 3.14 High-resolution (0.3") Very Large Array map of CO(J=2→1) emission from the z=4.12 quasar PSS J2322+1944, tracing cold molecular gas in its host galaxy. Gravitational lensing into a full Einstein ring makes this system easier to detect and map. The new capabilities of Expanded Very Large Array and ALMA will make it possible to extend such work to wider ranges in redshift and to target more typical high-redshift galaxies which are neither extremely luminous nor highly lensed. SOURCE: D.A. Riechers, F. Walter, B.J. Brewer, C.L. Carilli, G.F. Lewis, F. Bertoldi, and P. Cox, 2008, A molecular Einstein ring at z=4.12: Imaging the dynamics of a quasar host galaxy through a cosmic lens. The Astrophysical Journal 686(2):851 Reproduced by permission of the AAS.

Galaxies Across Cosmic Time (GCT)

GCT 1. HOW DO COSMIC STRUCTURES FORM AND EVOLVE?

- What is the structure of dark matter halos on galaxy, group, and cluster scales?
- What is the origin of the observed correlations among the fundamental properties of galaxies and of clusters, and how do they evolve with time?

- Maser SBMH masses
- Strong lensing

- It is *important* to measure supermassive black hole masses in hundreds or even thousands of systems using spatially resolved spectroscopy with adaptive optics on ELOITs, centimeter-wave maser observations with very long baseline arrays supplemented by large aperture dishes, and/or reverberation mapping of AGN. (See similar conclusion for the third key question, GCT 3.)

A precise study of the mass function of substructures on galaxy scales can also be done with radio interferometers, which can image strong galaxy-scale gravitational lenses to constrain the mass distribution within galaxies. Compared to optically imaged lenses, fewer radio lenses are bright enough for this technique, but the spatial resolution is far superior to even optical imaging from space. Because the incidence of lensing rises sharply with increasing spatial resolution, it will eventually be possible to study very large samples of lenses with high resolution radio imaging, with sensitive facilities that survey a large fraction of the sky. This kind of study can start now with existing and/or upgraded radio facilities, and will reach truly powerful levels with future facilities. The panel concluded:

- It is *important* to obtain Very Long Baseline Array (VLBA), Expanded Very Large Array (EVLA), e-Merlin, and/or ALMA imaging of at least a few hundred new galaxy-scale lenses. The development of a large-collecting-area radio facility that can survey a large fraction of the sky with subarcsecond resolution will increase the number of accessible lenses by several orders of magnitude.

Galaxies Across Cosmic Time (GCT)

GCT 2. HOW DO BARYONS CYCLE IN AND OUT OF GALAXIES, AND WHAT DO THEY DO WHILE THEY ARE THERE?

- How do galaxies acquire gas across cosmic time?
- What processes regulate the conversion of gas to stars as galaxies evolve?
- How are the chemical elements created and distributed?
- Where are the baryons as a function of redshift?

- It is *most important* to detect CO emission from a representative sample of typical star-forming galaxies from $z \sim 1$-3, to develop technology for faster spectroscopic follow-up in the (sub)millimeter, and to develop large-collecting-area facilities to study HI in emission at $z \sim 1$-3.

- It is *very important* to do sensitive radio and (sub)millimeter continuum mapping over large areas, preferably coincident with a near-IR (rest-frame optical) spectroscopic survey such as the one described above, and to carry out far-IR spectroscopy of luminous dusty galaxies.

- CO surveys at $z = 1$-3
- Develop capability for HI surveys at $z = 1$-3
- Radio and (sub)mm continuum wide area survey
- Far-IR spectroscopic survey of luminous dusty galaxies

Galaxies Across Cosmic Time (GCT)

GCT 3. HOW DO BLACK HOLES GROW, RADIATE AND INFLUENCE THEIR SURROUNDINGS?

- How do black holes grow over cosmic time?
- How do the quantity and form of energy production in accreting systems depend on black hole mass, accretion rate, and spin?
- How does black hole feedback shape the evolution of cosmic structures?

- High z radio galaxies
- Reverberation mapping of AGN
- High resolution imaging of jets

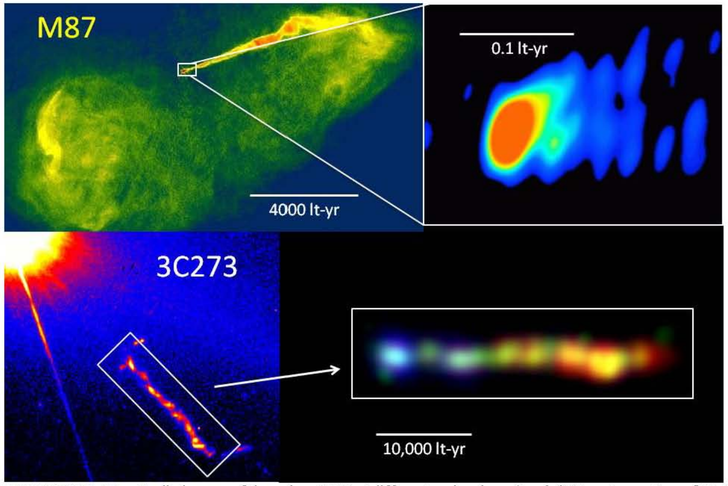


FIGURE 3.16 *Top:* Radio images of the galaxy M87 at different scales show (*top left,* Very Large Array [VLA]) giant, bubble-like structures of radio emission powered by the jets from the galaxy's central black hole and (*top right*) Very Long Baseline Array image of the jet being formed into a narrow beam within a hundred Schwarzschild radii of the black hole. The scale of each image is shown by white bars; 1,000 light-years is about 60 million times the distance from Earth to the Sun, and 0.1 light-year is about 1,000 Schwarzschild radii for M87's black hole mass of 3×10^8 M_{Sun}. SOURCE: NASA, National Radio Astronomy Observatory/National Science Foundation, John Biretta (STScI/JHU), and Associated Universities, Inc. *Bottom:* HST optical image of the quasar 3C 273 and its kiloparsec-scale jet (*bottom left*) and a multiwavelength Chandra/HST/Spitzer/VLA image of the jet alone (*bottom right*). The jet emission is synchrotron radiation from energetic electrons accelerated by the jet's magnetic field, and extends nearly 40,000 light-years across the sky. The highest energy particles, which radiate X-rays (blue), lose their energy quickly, whereas the lower-energy electrons that radiate optical (green), infrared (red), or radio (yellow) light persist to the end of the jet. Unresolved gamma-ray emission is also detected (e.g., with Fermi) from these and other AGN and is important for understanding the kinetic energy of jets. Calculating the electron energy from modeling the emission constrains the jet power, which is essential to understanding jet formation and propagation. SOURCE: *Top:* NASA, National Radio Astronomy Observatory/National Science Foundation, John Biretta (STScI/JHU), and Associated Universities, Inc. *Bottom left:* NASA/STScI. *Bottom right:* NASA/JPL-Caltech/Yale Univ.

Galaxies Across Cosmic Time (GCT)

GCT 4. WHAT WERE THE FIRST OBJECTS TO LIGHT UP THE UNIVERSE, AND WHEN DID THEY DO IT?

- Where and when did the first objects form?
- When did the first galaxies emerge and what were they like?
- How did these first objects reionize the universe?

GCT Discovery Area—The Epoch of Reionization

- It is *most important* to develop new capabilities to observe redshifted 21-cm HI emission, building on the legacy of current projects and increasing sensitivity and spatial resolution to characterize the topology of the gas at reionization.
- It is *very important* to do near-infrared absorption-line spectroscopy with JWST, ELOITs, and 10-meter-class telescopes to probe the conditions of the IGM during the epoch of reionization.
- It is *important* to measure the CMB E-mode polarization with Planck and possibly follow-on missions.
- It is *very important* to do multiwavelength surveys to detect galaxies, quasars, and GRBs residing in the late stages of reionization at $6 < z < 8$, including near-infrared surveys for galaxies and quasars, hard X-ray or gamma-ray monitors for GRBs, and time-variability surveys for supernovae or hypernovae.
- It is *important* for ALMA to have the capability to search for [CII] and [OI] fine structure line emission at redshifts $z > 6$.

- CMB
- Dark Ages and reionization HI
- $z > 6$ galaxies, quasars

Science Frontier Panel on Planetary Systems and Star Formation (PSF)

Questions:

- How do stars form?
- How do circumstellar disks evolve and form planetary systems?
- How diverse are planetary systems?
- Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?
- *Discovery area:* Identification and characterization of a nearby habitable exoplanet

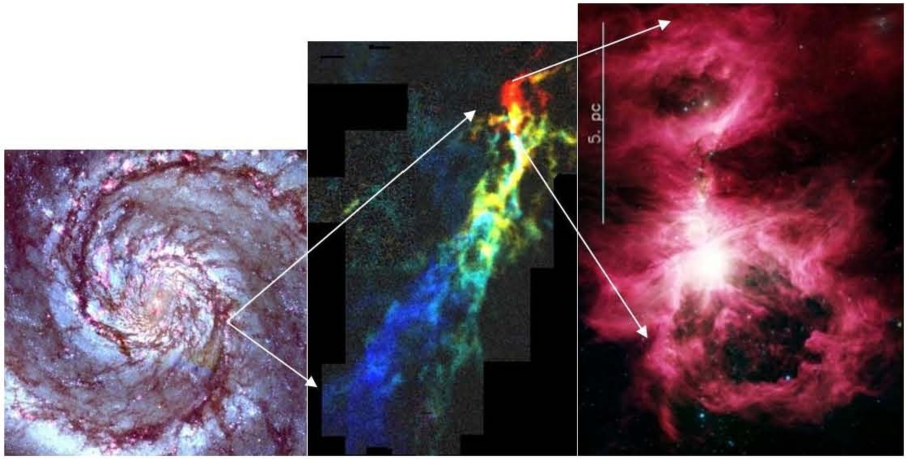


FIGURE 4.1 Schematic of the hierarchy of star formation. *Left*: Hubble Space Telescope image of the spiral galaxy M51, with Hα emission (in red) tracing the massive star-forming regions with a pixel scale equivalent to 5 pc. *Center*: the nearby Orion A molecular cloud traced by ^{13}CO $J = 1 \rightarrow 0$ emission, where the colors represent radial Doppler velocity. *Right*: the Orion Nebula Cluster as seen by the IRAC infrared camera on the *Spitzer* Space Telescope. SOURCE: *Left:* Scoville, N.Z., Polletta, M., Ewald, S., Stolovy, S.R., Thompson, R., and Rieke, M. 2001. High-Mass, OB Star Formation in M51: Hubble Space Telescope Hα and Paα Imaging. *Astrophys. J.* 122(6):3017-3045. Reproduced by permission of the AAS. *Center:* Bally, J. 2008. Overview of the Orion Complex. In *Handbook of Star Forming Regions Vol. I*. B. Reipurth, ed. San Francisco: Astronomical Society of the Pacific. Reproduced by kind permission of the Astronomical Society of the Pacific. *Right:* NASA/JPL-Caltech/Univ. of Toledo.

Planetary Systems and Star Formation (PSF)

How Do Stars Form?

- Extensive dust and molecular-line emission surveys of massive giant molecular clouds spanning spatial scales from 100 to 0.1 pc at distances greater than 5 kpc, and
- Complementary studies of the young stellar populations spawned in these regions, conducted by means of infrared surveys with spatial resolution at least 0.1 arcsec to reduce source confusion in clusters, with probing sufficiently faint to detect young brown dwarfs.

In the next stage of star formation, the dense structures in molecular clouds fragment into self-gravitating "cores" that are the direct progenitors of stars. There is mounting evidence from nearby star-forming regions that the distribution of core masses may be directly related to the resulting distribution of stellar masses, although some subsequent fragmentation likely produces binaries and very low mass objects. This may occur especially during the final stage of star formation through disk accretion. To explore this evolution and to improve core-mass spectra and characterize the core properties that may lead to subsequent fragmentation into stars, the panel recommends the following:

- Deep surveys of cores down to sizes of 0.1 pc at millimeter and submillimeter wavelengths in diverse star-forming environments out to distances of several kiloparsec (kpc), using both interferometers and large single-dish telescopes, far-infrared imaging and spectroscopy from spaceborne telescopes, and polarimetry to determine the role of magnetic fields.

- Dust and molecular studies of GMCs => cores

Planetary Systems and Star Formation (PSF)

How Do Circumstellar Disks Evolve and Form Planetary Systems?

- Studies of protoplanetary disks in nearby star-forming regions at resolutions below 100 milliarcsec, with every effort to achieve 10 milliarcsec resolution, at millimeter, submillimeter, infrared, and optical wavelengths, in order to map disk structure on spatial scales of approximately 1-10 AU;

- Imaging debris disks in optical and near-infrared scattered light on 8-m-class telescopes and in thermal dust emission at submillimeter wavelengths with ALMA and other interferometric arrays in order to search for resonant structures, gaps, and other features caused by the gravitational perturbations of planets, allowing the inference of unseen bodies and constraining their masses.

- Expanded theoretical efforts and simulations, with a detailed treatment of observational tracers to test theories, for developing an understanding of mass transport within disks and the processes of coagulation and accretion that lead to planet formation; and
- Major new efforts in chemical modeling and laboratory astrophysics to contribute to the understanding of the chemistry underlying molecule formation in the wide-ranging conditions in disks. In particular, laboratory studies of molecular spectra in the poorly studied far-infrared and submillimeter-wavelength regions of the spectrum are urgently needed to allow understanding and interpretation of the vast new array of spectral lines that are being detected by the Herschel mission and will be found by ALMA.

- Protoplanetary disks
- Debris disks
- Mass transport/accretion
- Laboratory astrophysics

Planetary Systems and Star Formation (PSF)

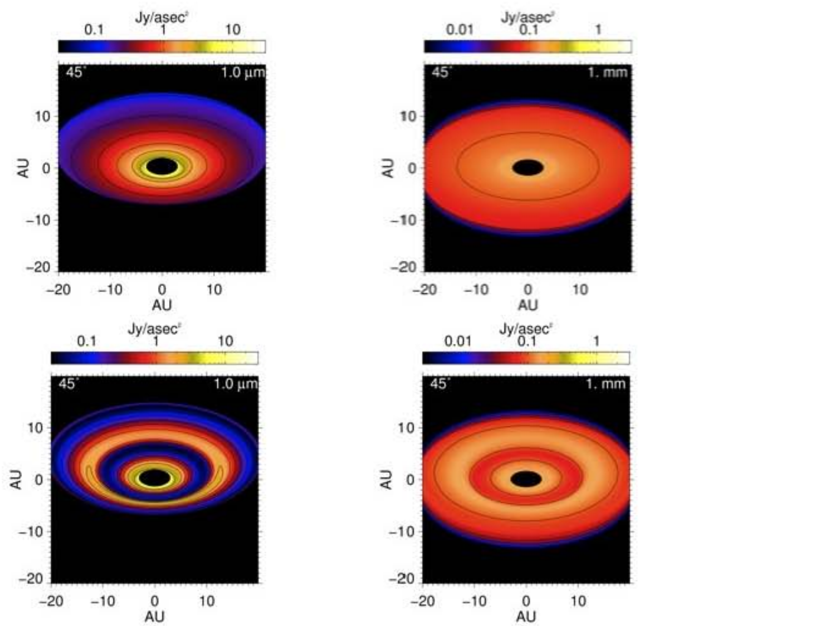


FIGURE 4.9 Surface brightness distributions and gap contrasts in both scattered light and thermal emission of the inner 20 AU of a protoplanetary disk around a 1 Myr old solar mass star, tipped by 45° to the line of sight. The upper panels show the unperturbed disk, at 1 µm (left) and at 1mm (right). In the lower panels the disk has a 4 AU wide gap at 10 AU, created by a 100 Earth-mass planet, showing a contrast ratio of about 0.1 in scattered light and 0.5 in thermal emission with respect to the rest of the disk. At the distance of the Taurus star formation region each image is 0.28 arcsec wide. Assuming a GSMT with diameter 30 m operating at 1 µm, the instrumental point-spread function would be 1.1 AU in diameter (FWHM), and the surface brightness of 1 Jy arcsec^{-2} corresponds to a contrast, with respect to the stellar image, of about 3×10^{-3}. Expected noise levels at 1 Jy arcsec^{-2} are of order 1 hour with ALMA; GSMT times are much shorter, depending upon backgrounds. SOURCE: Courtesy of H. Jang-Condell, private communication.

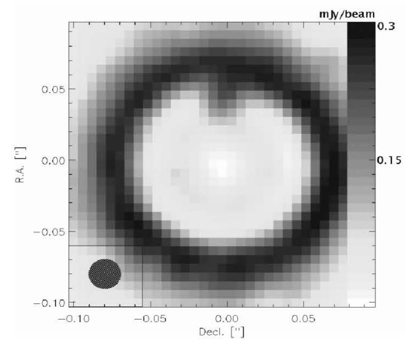


FIGURE 4.11 Simulation of an 8-hour, 345 GHz ALMA observation of a $0.01M_\odot$ circumstellar disk, with a recently formed planet of $1M_J$, at 12:00, orbiting 5 AU away from a $0.5M_\odot$ star (not shown). The distance to this hypothetical system is 100 pc. Most of the flux detected at the planet's position is from material about to be accreted by the planet. SOURCE: Wolf, S. and D'Angelo, G. 2005. On the Observability of Giant Protoplanets in Circumstellar Disks. *Astrophys. J.* 619, 1114-1122. Reproduced by permission of the AAS.

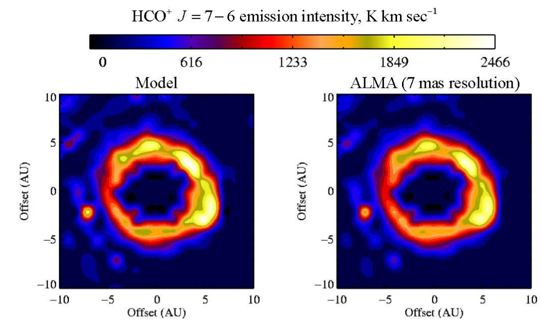


FIGURE 4.8 A gravitationally unstable disk imaged *in line emission from very dense gas* in HCO^+ J = 7-6 (λ = 480 µm) for a $0.09M_\odot$ disk around a $1M_\odot$ star at a distance of 140 pc, viewed face-on. *Left:* 3-D model at full resolution shows a Jovian-mass collapsing fragment in the outer ring. *Right:* the same scene convolved to the resolution of ALMA in its longest-baseline configuration, with 0.007 arcsec resolution (1 AU at 140 pc). At ALMA's projected sensitivity, the noise level in this image would be 100 K km/sec in 16 hours of observation; the protoplanetary fragment would be marginally detected (3 sigma) in about 1 hour. SOURCE: Narayanan, D., Kulesa, C.A., Boss, A., and Walker, C.K. 2006. Molecular Line Emission from Gravitationally Unstable Protoplanetary Disks. *Astrophys. J.* 647, 1426-1436. Reproduced by permission of the AAS.

- Protoplanetary disks
- Debris disks

Science Frontier Panel on Stars and Stellar Evolution (SSE)

Questions:

1. How do rotation and magnetic fields affect stars?
2. What are the progenitors of Type Ia supernovae and how do they explode?
3. How do the lives of massive stars end?
4. What controls the mass, radius, and spin of compact stellar remnants?
5. *Unusual discovery potential:* time-domain astronomy—in which the technology on the horizon is well matched to the many timescales of stellar phenomena.

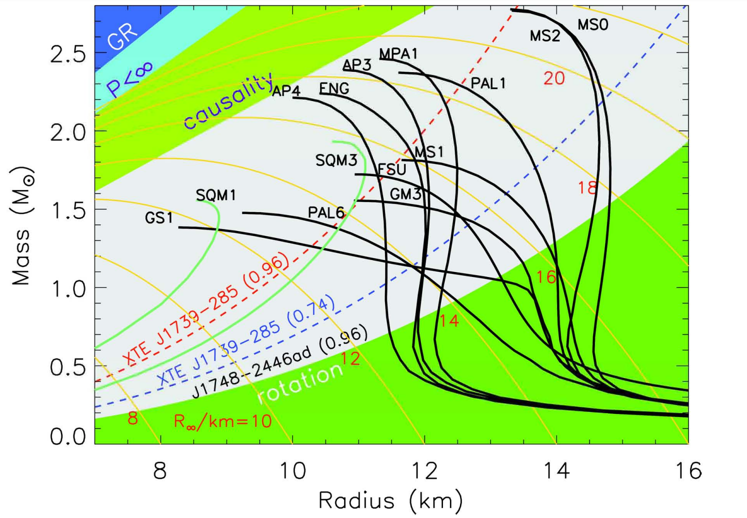
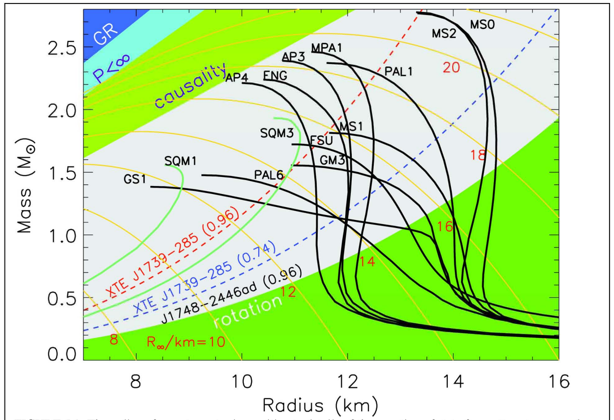


FIGURE 5.8 The radius of a neutron star is sensitive to details of the equation of state for matter at near-nuclear densities. Measurement of M and R for neutron stars in the next decade should suffice to rule out some of the equations of state displayed here (as black and green curves) in a figure from Lattimer and Prakash 2007. The green region at the lower right is excluded from observations of pulsar J1748-2446ad. The recent discovery of pulsars with $M>1.6\ M_\odot$ rules out equation of state models that do not extend to such high masses. SOURCE: Reprinted from Physics Reports 442(1-6), J.M. Lattimer and M. Prakash, Neutron star observations: Prognosis for equation of state constraints, pp. 109-165, Copyright 2007, with permission from Elsevier.

Stars and Stellar Evolution (SSE)



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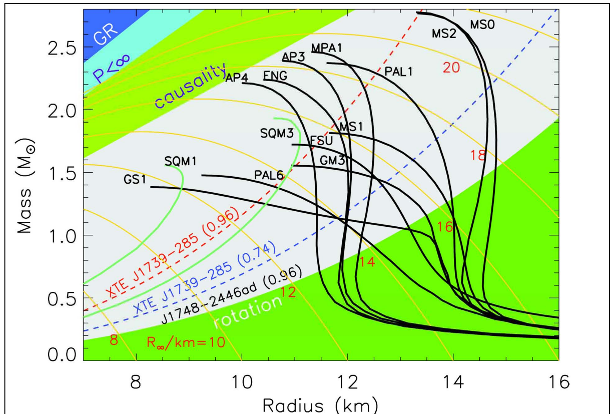
- Radio gyrosynchrotron observations of the magnetic structure of the Sun
- Multiwavelength studies of solar activity
- Radio studies of SNe
- Masses of neutron stars from pulsar timing

Stars and Stellar Evolution (SSE)



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Electromagnetic Counterparts to Gravitational Wave Sources

In the coming decade, it is likely that transient gravitational wave sources will be discovered by experiments such as Advanced LIGO and VIRGO (a gravitational wave detector at the European Gravitational Observatory), with lower frequency gravitational wave sources perhaps becoming detectable towards the end of the decade. To optimize the astrophysics that results from such detections, it is critical to have nearly simultaneous electromagnetic observations. Wide field of view cameras are essential given the rather poor localizations provided by gravity wave detectors (~ fractions of a square degree). A unique electromagnetic counterpart temporally and spatially coincident with the gravitational wave source would provide more confidence in the gravitational wave detection. Combined gravitational wave and electromagnetic observations could potentially provide detailed information about stellar sources including NS-NS mergers, BH-BH mergers, short gamma-ray bursts, and (perhaps) core-collapse supernovae. This information is unique given the gravitational wave constraints on the masses and spins (magnitudes and direction) of the objects.

Radio Transients

Stars of all kinds produce a surprisingly wide variety of non-thermal radio emission from time scales of nanoseconds (the giant pulses from the Crab pulsar), to months (the radio afterglows of supernovae). Recently, a handful of relatively small-scale radio surveys have uncovered new forms of transients from known sources, such as extremely rare millisecond duration pulses from rotating neutron stars (the so-called RRATs), and bright coherent emission from brown dwarfs. Other surveys have found unidentified radio transients in extragalactic blank fields and toward the galactic center. Yet these surveys have covered either only tiny fractions of the sky or a very small range of time scales. The situation is improving with the development of LOFAR, LWA, MWA, and ATA-42. As radio fields-of-view continue to increase and computing capability grows to allow wide-field, rapid cadence, radio imaging, new surveys will uncover many more transient events of both known and unknown origin. These events have the potential to tell us about particle acceleration, stellar magnetic fields and rotation, strong-field gravity, the interstellar and intergalactic media, the violent deaths of stars, and possibly physics beyond the standard model.

New Worlds, New Horizons

TABLE I Summary of Science Frontiers Panels' Findings

Panel		Science Questions	Area(s) of Unusual Discovery Potential
Cosmology and Fundamental Physics	CFP 1	How Did the Universe Begin?	Gravitational Wave Astronomy
	CFP 2	Why Is the Universe Accelerating?	
	CFP 3	What Is Dark Matter?	
	CFP 4	What Are the Properties of Neutrinos?	
Galactic Neighborhood	GAN 1	What Are the Flows of Matter and Energy in the Circumgalactic Medium?	Time-Domain Astronomy Astrometry
	GAN 2	What Controls the Mass-Energy-Chemical Cycles Within Galaxies?	
	GAN 3	What Is the Fossil Record of Galaxy Assembly from the First Stars to the Present?	
	GAN 4	What Are the Connections Between Dark and Luminous Matter?	
Galaxies Across Cosmic Time	GCT 1	How Do Cosmic Structures Form and Evolve?	The Epoch of Reionization
	GCT 2	How Do Baryons Cycle in and out of Galaxies, and What Do They Do While They Are There?	
	GCT 3	How Do Black Holes Grow, Radiate, and Influence Their Surroundings?	
	GCT 4	What Were the First Objects to Light Up the Universe, and When Did They Do It?	
Planetary Systems and Star Formation	PFS 1	How Do Stars Form?	Identification and Characterization of Nearby Habitable Exoplanets
	PFS 2	How Do Circumstellar Disks Evolve and Form Planetary Systems?	
	PFS 3	How Diverse Are Planetary Systems?	
	PFS 4	Do Habitable Worlds Exist Around Other Stars, and Can We Identify the Telltale Signs of Life on an Exoplanet?	
Stars and Stellar Evolution	SSE 1	How Do Rotation and Magnetic Fields Affect Stars?	Time-Domain Surveys
	SSE 2	What Are the Progenitors of Type Ia Supernovas and How Do They Explode?	
	SSE 3	How Do the Lives of Massive Stars End?	
	SSE 4	What Controls the Mass, Radius, and Spin of Compact Stellar Remnants?	

The Science Frontier
discovery areas and principal questions

Discovery areas:

- Identification and characterization of nearby habitable exoplanets
- Gravitational wave astronomy
- Time-domain astronomy
- Astrometry
- The epoch of reionization

Questions:

- How did the universe begin?
- What were the first objects to light up the universe and when did they do it?
- How do cosmic structures form and evolve?
- What are the connections between dark and luminous matter?
- What is the fossil record of galaxy assembly and evolution from the first stars to the present?
- How do stars and black holes form?
- How do circumstellar disks evolve and form planetary systems?
- How do baryons cycle in and out of galaxies and what do they do while they are there?
- What are the flows of matter and energy in the circumgalactic medium?
- What controls the mass-energy-chemical cycles within galaxies?
- How do black holes work and influence their surroundings?
- How do rotation and magnetic fields affect stars?
- How do massive stars end their lives?
- What are the progenitors of Type Ia supernovae and how do they explode?
- How diverse are planetary systems and can we identify the telltale signs of life on an exoplanet?
- Why is the universe accelerating?
- What is dark matter?
- What are the properties of the neutrinos?
- What controls the masses, spins and radii of compact stellar remnants?

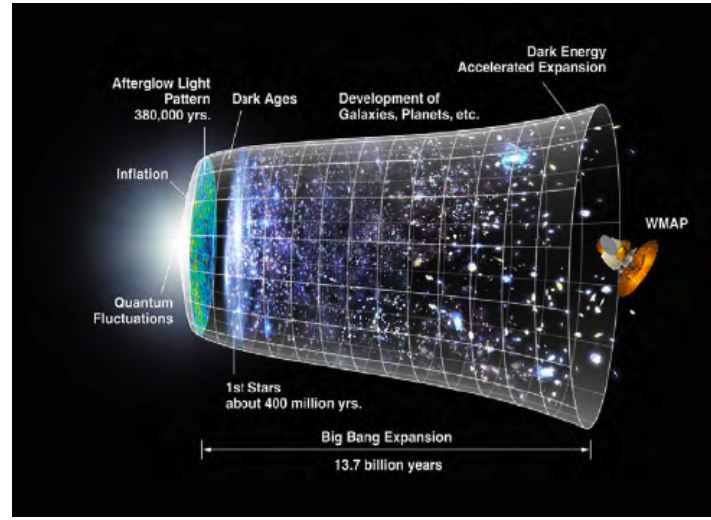
SFP => NWNH Science Objectives

- Building on the science priorities identified by the survey, the recommended program is organized by three science objectives that represent its scope:
  - Cosmic Dawn
  - New Worlds
  - Physics of the Universe

- Success in attaining these science goals will enable progress on a much broader front
- Also foster unanticipated discoveries

Cosmic Dawn

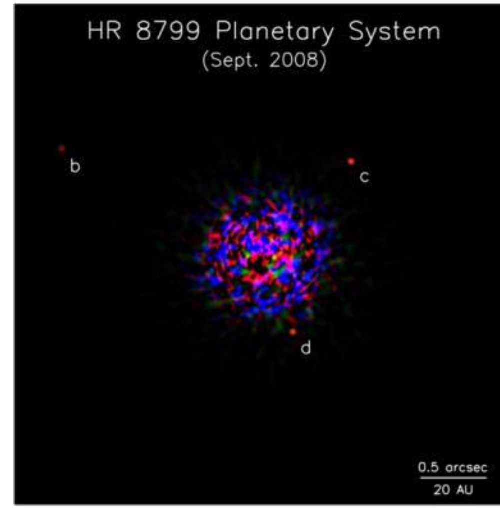
Searching for the first stars, galaxies, and black holes



- We have learned much about the history of the universe, from the Big Bang to today
- A great mystery now confronts us: when and how the first galaxies formed and the earliest stars started to shine - our cosmic dawn
- JWST, ALMA and radio telescopes already under construction will help point the way
- Approaches:
  - Locating "reionization" – finding the epoch ~0.5 billion years, when light from the first stars split interstellar hydrogen atoms into protons and electrons
  - "Cosmic paleontology" – finding the rare stars with the lowest concentrations of heavy elements

New Worlds

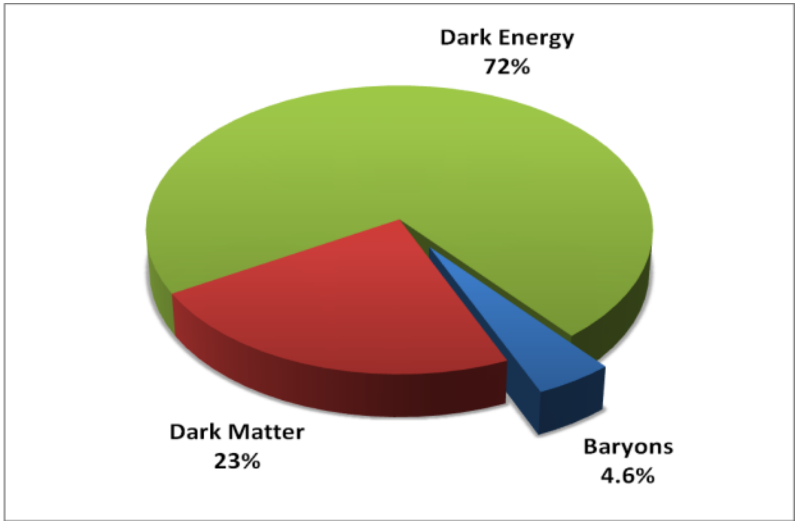
Seeking nearby, habitable planets



- Nearly 500 extrasolar planets now detected - extraordinarily rapid progress
  - Huge range of properties exhibited, surprisingly different from those in our own solar system
  - Many ongoing approaches seek new "Earths" – potentially habitable rocky planets with liquid water and oxygen
  - New techniques being developed
- Kepler data adds over 300 "candidates" to the list, including many less than twice the size of Earth
- Next great step forward: understand frequency of different types of planets and lay scientific and technical groundwork to inform future strategies for detailed study of nearby Earth-like planets

Physics of the Universe

Understanding Scientific Principles



- Determine properties of dark energy, responsible for perplexing acceleration of present-day universe
- Reveal nature of mysterious dark matter, likely composed of new types of elementary particles
- Explore epoch of inflation, earliest instants when seeds of structure in the universe were sown
- Test Einstein's general theory of relativity in new important ways by observing black hole systems and detecting mergers